PERGAMON

Renewable and Sustainable Energy Reviews
6 (2002) 557–572

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

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Review of solar and low energy cooling technologies for buildings

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Received 11 January 2002; received in revised form 3 June 2002; accepted 3 June 2002

Abstract

The objective of this paper is to examine solar cooling and low energy cooling technologies. A brief review of various cooling systems is presented, including solar sorption cooling, solar-mechanical systems, solar related air conditioning, and other low energy cooling technologies. The relative efficiencies and applications of the various technologies are presented. These technologies can be utilized to reduce both the energy consumption and environmental impact of mechanical cooling systems.

Contents

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PII: S1364-0321(02)00016-3

1. Introduction

The quest to accomplish a safe and comfortable environment has always been one of the main preoccupations of the human race. In ancient times people used experience gained over many years to make the best use of available resources to achieve adequate living conditions. The Greek historian Xenophon in his 'Memorabilia' records some of the teachings of the Greek philosopher Socrates (470–399 BC) regarding correct orientation of dwellings in order to have houses cool in summer and warm in winter [1]. Central heating was pioneered by the Romans using double floors through whose cavity the fumes of a fire were passed. Also in Roman times windows were covered for the first time with materials like mica or glass. Thus, light was admitted in the house without letting in wind and rain [2]. The Iraqis on the other hand utilized the prevailing wind to take advantage of the night cool air and provide a cooler environment during the day [3]. Additionally, running water was employed to provide some evaporative cooling.

As late as the 1960s though, house comfort conditions were only for the few. From then onwards central air conditioning systems became common in many countries due to the development of mechanical refrigeration and the rise of the standard of living. The oil crises of the 1970s stimulated intensive research aimed at reducing energy costs. Also, global warming and ozone depletion and the escalating costs of fossil fuels over the last few years, have forced governments and engineering bodies to re-examine the whole approach to building design and control. Energy conservation, in the sense of fuel saving, is also of great importance.

During recent years research aimed at the development of technologies that can offer reductions in energy consumption, peak electrical demand and energy costs without lowering the desired level of comfort conditions has intensified. Alternative cooling technologies are being developed which can be applied to residential and commercial buildings, in a wide range of weather conditions. These include night cooling with ventilation, evaporative cooling, desiccant cooling, slab cooling etc. The design of buildings employing low energy cooling technologies, however, presents difficulties, and requires advanced modeling and control techniques to ensure efficient operation.

Another method that can be used for reducing the energy consumption is ground cooling. This is based on the heat–loss dissipation from a building to the ground,

which, during the summer, has a lower temperature than the ambient. This dissipation can be achieved either by direct contact of an important part of the building envelope with the ground, or by blowing air that has first been passed through an earth-to-air heat exchanger into the building [4].

The role of designers and architects is very important too, especially with respect to solar energy control, the utilization of thermal mass and correct ventilation of a building. In effective solar energy control, summer heat gains must be reduced while winter solar heat gains must be maximized. This can be achieved by the proper orientation and shape of the building, the use of shading devices and the selection of proper construction materials. Thermal mass, especially in hot climates with diurnal variation of ambient temperatures exceeding 10 °C, can be used to reduce the instantaneous high cooling loads, reduce energy consumption and attenuate indoor temperature swings. Correct ventilation can enhance the roles of both solar energy control and thermal mass.

Reconsideration of the building structure, the readjustment of capital cost allocations (i.e., investing in energy conservation measures that may have a significant influence on thermal loads) and improvements in equipment and maintenance, can minimize the energy expenditure and improve thermal comfort.

In intermediate seasons in hot dry climates, processes like evaporative cooling can offer energy conservation opportunities. However in summertime, due to the high temperatures, low energy cooling technologies cannot alone satisfy the total cooling demand of domestic dwellings. For this reason active cooling systems are required. Vapour compression cooling systems are usually used, powered by electricity, which is expensive, and its production depends entirely on fossil fuel. In such climates one of the sources abundantly available is solar energy, which could be used to power an active solar cooling system based on the absorption cycle. The problem with solar absorption machines is that they are expensive compared to vapour compression machines, and are not readily available in the small capacity range applicable to domestic cooling applications. Reducing the use of conventional vapour compression air-conditioning systems will also reduce their effect on both, global warming and ozone layer depletion.

The integration of the building envelope with an absorption system should offer better control of the internal environment. Two basic types of absorption units are available; ammonia-water and lithium bromide (LiBr)-water units. The latter are more suitable for solar applications since their operating (generator) temperature is lower and thus more readily obtainable with low-cost solar collectors [5].

The objective of this paper is to review the various solar and low energy cooling technologies with respect to their operational characteristics and performance, in order to facilitate selection of the most appropriate system for a given application.

2. Solar cooling systems

Solar cooling systems can be classified into three categories: namely, solar sorption cooling, solar-mechanical systems and solar-related systems.

2.1. Solar sorption cooling

Sorbents are materials that have an ability to attract and hold other gases or liquids. This characteristic makes them very useful in chemical separation processes. Desiccants are sorbents that have a particular affinity for water. The process of attracting and holding moisture is described as either absorption or adsorption, depending on whether the desiccant undergoes a chemical change as it takes on moisture. Absorption changes the desiccant as for example the table salt, which changes from a solid to a liquid as it absorbs moisture. Adsorption, on the other hand, does not change the desiccant except by the addition of the weight of water vapour, similar in some ways to a sponge soaking up water [6].

Absorption systems are similar to vapour-compression air conditioning systems but differ in the pressurization stage. In general, an evaporating refrigerant is absorbed by an absorbent on the low-pressure side. Combinations include lithium bromide-water (LiBr-H_2O) where water vapour is the refrigerant and ammonia-water (NH_3-H_2O) systems where ammonia is the refrigerant [7].

The pressurization is achieved by dissolving the refrigerant in the absorbent in the absorber section (Fig. 1). Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump.

The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way, the refrigerant vapour is compressed without the need for a large amount of mechanical energy that vapour-compression air conditioning systems demand.

The remainder of the system consists of a condenser, expansion valve and evaporator, which function in a similar way as in a vapour-compression air conditioning system.

The NH_3-H_2O system is more complicated than the LiBr-H_2O since it needs a rectifying column that assures that no water vapour enters the evaporator where it could freeze. The NH_3-H_2O system requires generator temperatures in the range of 125 °C–170 °C with air-cooled absorber and condenser and 95 °C–120 °C when

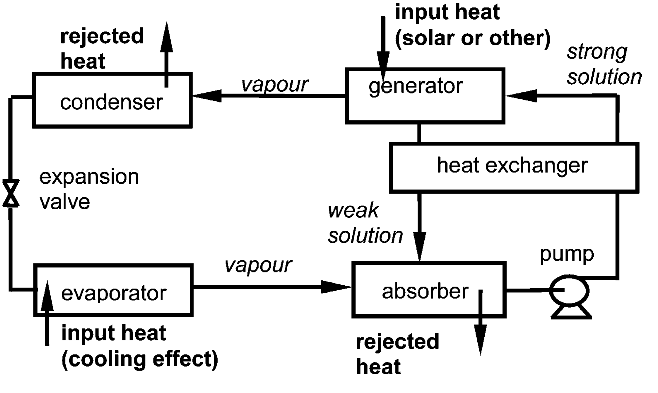

Fig. 1. Basic principle of the absorption air conditioning system.

water-cooling is used. These temperatures cannot be obtained with flat-plate collectors. The coefficient of performance (COP), which is defined as the ratio of the cooling effect to the heat and electricity inputs, is between 0.6–0.7 for single effect (stage) systems. The LiBr-H_2O system operates at a generator temperature in the range of 70 °C–95 °C with water used as a coolant in the absorber and condenser and has COP higher than the NH_3-H_2O systems, 0.6–0.8 for single effect systems [8]. A disadvantage of LiBr-H_2O systems is that their evaporator cannot operate at temperatures much below 5 °C since the refrigerant is water vapour.

Adsorption cooling is the other group of sorption air conditioners that utilizes an agent (the adsorbent) to adsorb the moisture from the air (or dry any other gas or liquid) and then uses the evaporative cooling effect to produce cooling. Solar energy can be used to regenerate the drying agent. Solid adsorbents include silica gels, zeolites, synthetic zeolites, activated aluminas, carbons and synthetic polymers [9]. Liquid adsorbents can be triethylene glycol solutions of lithium chloride and lithium bromide solutions.

Many cycles have been proposed for adsorption cooling and refrigeration [10]. The principle of operation of a typical system is indicated in Fig. 2. The process followed at the points from 1 to 9 of Fig. 2, is traced on the psychrometric chart of Fig. 3. Ambient air is heated and dried by a dehumidifier from point 1 to 2, regeneratively cooled by exhaust air from 2 to 3, evaporatively cooled from 3 to 4 and introduced into the building. Exhaust air from the building is evaporatively cooled from 5 to 6, heated to 7 by the energy removed from the supply air in the regenerator, heated by solar or other source to 8 and then passed through the dehumidifier where it regenerates the desiccant.

The selection of the adsorbing agent depends on the size of the moisture load and the application.

Rotary solid desiccant systems are the most common for continuous removal of moisture from the air. The desiccant wheel rotates through two separate air streams. In the first stream the process air is dehumidified by adsorption, which does not change the physical characteristics of the desiccant, while in the second stream the

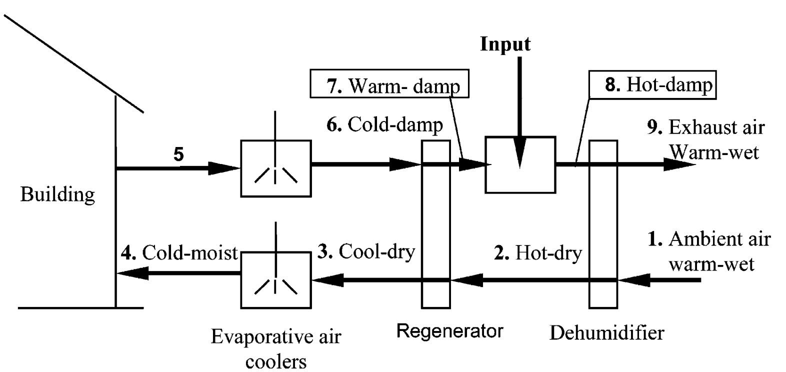

Fig. 2. Schematic of a solar adsorption system.

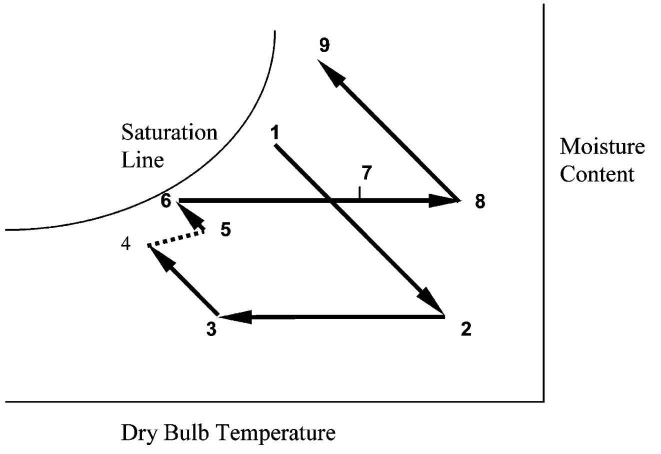

Fig. 3. Psychrometric diagram of a solar adsorption process.

reactivation or regeneration air, which is first heated, dries the desiccant. A schematic of a possible solar-powered adsorption system is illustrated in Fig. 4.

When the drying agent is a liquid, such as triethylene glycol, the agent is sprayed into an absorber where it picks up moisture from the building air. Then it is pumped through a sensible heat exchanger to a separation column where it is sprayed into a stream of solar heated air. The high temperature air removes water from the glycol, which then returns to the heat exchanger and the absorber. Heat exchangers are provided to recover sensible heat, maximize the temperature in the separator and minimize the temperature in the absorber. This type of cycle is marketed commercially and used in hospitals and large installations [8].

The energy performance of these systems depends on the system configuration, geometries of dehumidifiers, properties of adsorbent agent, etc., but generally the COP of this technology is around 1.0.

It should be noted however that in hot/dry climates the desiccant part of the system may not be required.

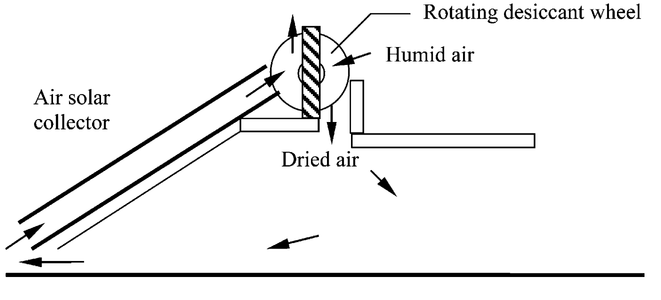

Fig. 4. Solar adsorption cooling system.

2.2. Solar-mechanical systems

These systems utilize a solar-powered prime mover to drive a conventional air-conditioning system. This can be done by converting solar energy into electricity by means of photovoltaic devices, and then utilize an electric motor to drive a vapour compressor. The photovoltaic panels have a low field efficiency of about 10–15%, depending on the type of cells used [11], which result in low overall efficiencies for the system.

The solar-powered prime mover can also be a Rankine engine. In a typical system, energy from the collector is stored, then transferred to a heat exchanger and finally energy is used to drive the heat engine. The heat engine drives a vapour compressor, which produces a cooling effect at the evaporator. As shown in Fig. 5, the efficiency of the solar collector decreases as the operating temperature increases, whereas the efficiency of the heat engine of the system increases as the operating temperature increases. The two efficiencies meet at point A (in Fig. 5) giving an optimum operating temperature for steady state operation. The combined system has overall efficiencies between 17 and 23%.

Due to the diurnal cycle, the cooling load varies and also the storage tank temperature changes through the day. Therefore, designing such a system presents appreciable difficulties. When a Rankine heat engine is coupled with a constant speed air conditioner, the output of the engine seldom matches the input required by the air conditioner. Therefore, auxiliary energy must be supplied when the engine output is less than that required, or otherwise, excess energy may be used to produce electricity for other purposes.

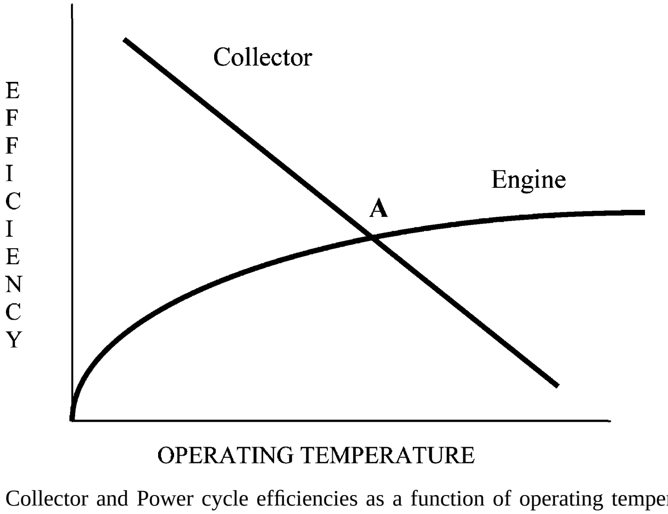

Fig. 5. Collector and Power cycle efficiencies as a function of operating temperature.

2.3. Solar related air conditioning

Some components of systems installed for the purpose of heating a building can also be used to cool it but without the direct use of solar energy. Examples of these systems can be:

2.3.1. Heat pumps

A heat pump is a device that pumps heat from a low temperature source to a higher temperature sink. Heat pumps are usually vapour compression refrigeration machines where the evaporator can take heat into the system at low temperature, and the condenser can reject heat from the system at high temperature. In the heating mode a heat pump delivers thermal energy from the condenser for space heating and can be combined with solar heating. In the cooling mode the evaporator extracts heat from the air to be conditioned and rejects heat from the condenser to the atmosphere, with solar energy not contributing to the energy for cooling. The performance characteristics of an integral type solar-assisted heat pump are given in [12].

2.3.2. Rock bed regenerator

Rock beds (or pebble beds) storage units of solar air heating systems can be night-cooled during summer to store ‘cold’ for use the following day. This can be accomplished by passing outside air during the night when the temperatures and humidities are low, through an optional evaporative cooler, through the pebble bed and to the exhaust. During the day, the building can be cooled by passing room air through the pebble bed. A number of applications using pebble beds for solar energy storage are given in [13]. For such systems airflow rates should be kept to a minimum so as to minimize fan power requirements without affecting the performance of the pebble bed. Therefore an optimization process should be followed as part of the design.

2.3.3. Alternative cooling technologies or passive systems

Passive cooling is based on the transfer of heat by natural means from a building to environmental sinks like clear skies, the atmosphere, the ground and water. The transfer of heat can be by radiation, naturally occurring wind, airflow due to temperature differences, conduction to the ground or conduction and convection to bodies of water. It is usually up to the designer to select the most appropriate type of technology for each application. The options depend on the climate type. Finally, other methods of cooling load reduction including hybrid methods, operated with mechanical energy and by passive means, can also be used, depending on the specific characteristics under consideration.

3. Other low energy cooling technologies

3.1. Night cooling

In this system, night cool air is used to remove heat from the interior of a building. The outdoor air can enter into the building naturally, mechanically or with both

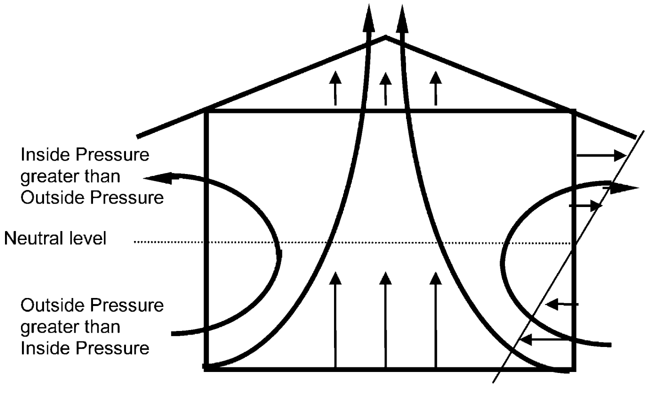

Fig. 6. Air circulation due to stack effect. Arrows indicate pressure differences [14].

methods. During natural ventilation (Fig. 6), air enters into the building through intentional openings left to utilize either the indoor/outdoor temperature differences (stack effect) or the wind pressures.

Fig. 7, indicates how the prevailing wind is utilized in a traditional Iraqi house, to take advantage of the night cool air and provide a cooler environment during the day. In mechanical ventilation a fan and a duct system can be used to force air into the building.

Natural night cooling is an unreliable method for air quality, quantity and controllability. Its effect depends largely on the magnitude of heat gains and ventilation rates.

Night cooling with mechanical ventilation is much more controllable and is especially suited to unoccupied buildings during the night (office buildings), where relatively high air flows can be used to maximize the cooling effect [15]. When designing such a system, fan power must be considered in relation to overall cooling effect it produces.

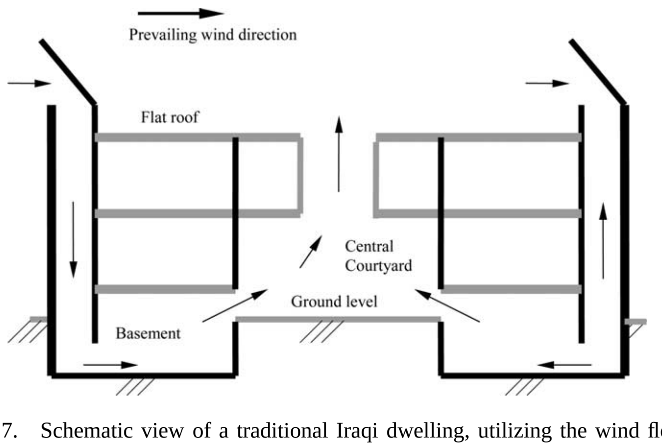

Fig. 7. Schematic view of a traditional Iraqi dwelling, utilizing the wind flow.

The building mass is of great importance when night cooling is used, since a large mass will absorb greater amounts of heat load during the day. Also, the interior surfaces of the building need to be exposed as much as possible to the airflow, and lightweight materials such as carpets and false ceilings should be replaced by installing thermally heavy dry coatings. In some cases, better results can be obtained when the airflow is directed through a false floor or through a cavity within the building.

3.2. Slab cooling

This technique utilizes the thermal capacity of the building structure to store a large amount of energy leading to a small variation of the structure's temperature. In this way, day-time heat gains are absorbed by the structure and stored until they can be purged with night cooling. At the moment, most Fabric Energy Storage systems (FES) utilize floor and ceiling slabs. The basic principle of FES is to bring air or water into contact with the slabs in the building envelope as indicated in Fig. 8. The FES systems provide flexibility to work with other technologies like natural and mechanical cooling, evaporative cooling etc.

Air slab cooling techniques include [3]:

1. The FES slab (Trade name Termodeck). This is a prefabricated rectangular concrete block with typical dimensions of 4 m length by 1.2 m width by 0.3 m depth. The interconnection of the hollow core slabs establishes the air paths, through which cooled or heated air is discharged via ceiling diffusers to the indoor spaces.
2. The plenum-and-slab system, which provides air through hollow core floor slabs, interconnected between a number of large air plenums. Operating experience indicated that this system is only suitable for floor slabs at the ground floor.
3. The hollow-core screed, which produces cross air paths between a layer of hollow-core screed and a solid concrete slab. The advantage of this system is that it can be retrofitted into an existing building and consists of square grids of semicircles,

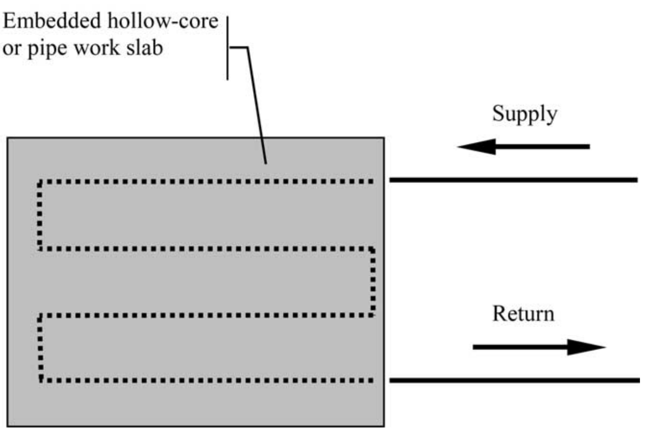

Fig. 8. Basic principle of Fabric Energy Storage system (FES).

37.5 mm in radius, covered with 75 mm thick screed. The narrow air channel design of this method may present difficulties in maintenance.

In general, the above methods provide low capital and operating cost but their potential depends on the level of overnight ambient air temperature and provides sensible cooling only.

In the case that water is used to cool the slab, the pipe-work can be in a layer of screed of about 75 mm thick or a layer of solid concrete slab exposed to the conditioned space. A heat exchanger, a chiller or any other apparatus can cool the circulating water but water leakage of the embedded piping and replacement of the embedded pipe-work due to corrosion and erosion problems are serious drawbacks of the method.

Additionally, condensation on surfaces that are below due point may result and should be considered when designing such a system.

3.3. Chilled ceilings

In this approach surfaces within the ceiling are cooled by chilled water circulation for the removal of heat gains, leaving ventilation and humidity control to the air-distribution system.

An essential feature of these systems is that the entering chilled water temperature should be above the room dew-point by at least 1.5 °C to allow for control tolerance, in order to avoid condensation from forming on the cooling surfaces. Typically, chilled ceiling systems have a flow water temperature of 14–15 °C and a temperature increase across the exchange device of 2–3 °C [16].

The cooling surfaces may take any number of forms and are classified into radiant panels, convective panels and chilled beams.

In the case of radiant and convective panels, the cooling surface covers large areas of the ceiling. The radiant panels depend mainly on radiation heat transfer between their surface and the conditioned space, and can be of a metal or concrete slap type. The radiant panels can be embedded within the false ceiling or be accommodated in shallow ceiling voids (Fig. 9).

Convective panels can be finned pipe coils, which are located within the void above the false ceiling. In this case the false ceiling is perforated or slotted with at

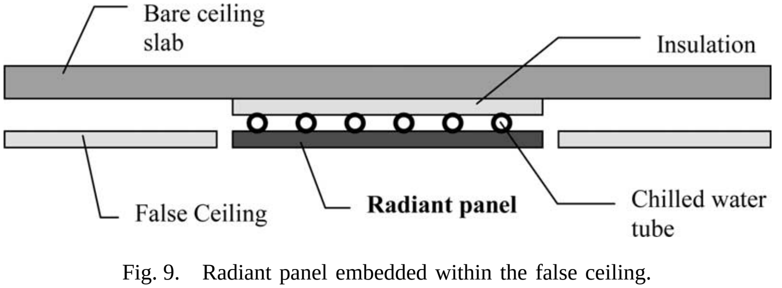

Fig. 9. Radiant panel embedded within the false ceiling.

least 20% free area, to the room space. Warm air rising into the ceiling void is cooled by the coil and then falls down in the room due to its higher density.

Chilled beams work in a similar manner to convective panels. In this case, the finned coils are located into a unit, which can also supply ventilation air (Fig. 10).

3.4. Evaporative air coolers

Evaporative air-cooling is achieved by evaporating water at ambient temperature into the air stream. With this method the air dry-bulb temperature is reduced along a line of constant wet-bulb temperature, resulting in an increase of the latent heat and air moisture content. Evaporative cooling can be achieved through direct air-cooling, indirect air-cooling, a combination of both and can also be combined with mechanical refrigeration systems and desiccant technologies.

In direct evaporative cooling systems, the water in an evaporative pad or from a fine water spray, evaporates directly into a supply of air stream, producing both cooling and humidification (Fig. 11). The maximum reduction in dry-bulb temperature is the difference between the entering air dry and wet bulb temperatures.

When the air is saturated, the air is cooled to the wet-bulb temperature and the process is 100% effective. System effectiveness is the depression of the dry-bulb temperature of the air leaving the apparatus divided by the difference between the dry and wet-bulb temperatures of the air. Evaporative cooling systems may be 85–90% effective. Direct evaporative cooling when used together with mechanical refrigeration can reduce cooling costs by between 25 and 40% [17].

Indirect evaporative air-cooling evaporates water into a secondary air stream through the channels of a heat exchanger. The heat exchanger cools air flowing in a primary stream. This results in sensible cooling only. Except in extreme dry climates, most indirect systems require several stages to further cool the primary air entering the conditioned spaces.

Indirect evaporative cooling can precede a direct evaporative stage and can reduce, in this way, the entering dry and wet bulb temperatures before the air enters the direct evaporative cooling unit [17].

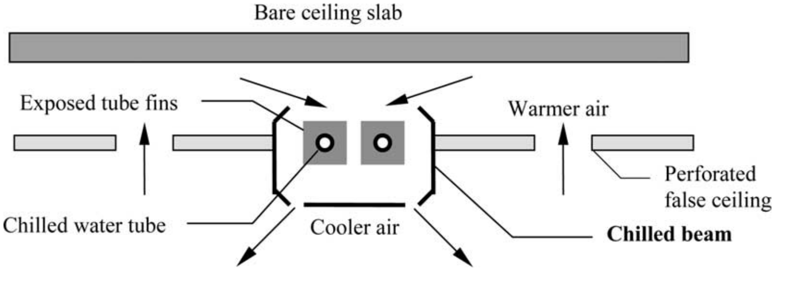

Fig. 10. Chilled beam.

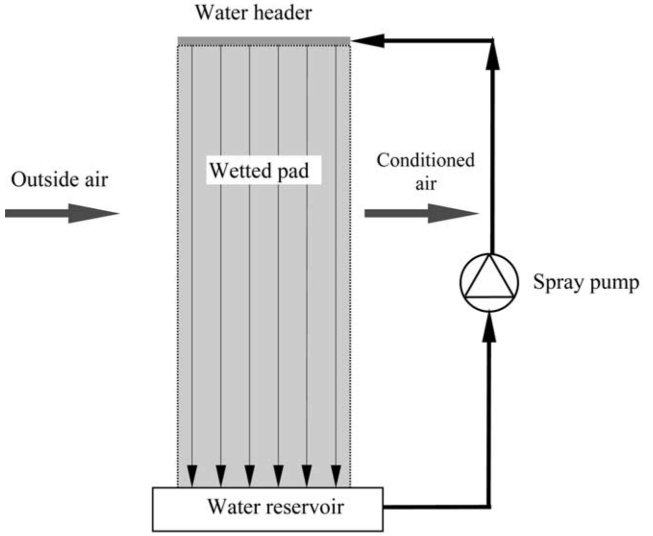

Fig. 11. Direct evaporative cooling diagram.

4. System evaluation

Table 1, summarizes the advantages and disadvantages of the cooling methods described above, as well as their performance and main uses.

5. Conclusions

The objective of the above work was to present various low energy cooling technologies that may be applied alone, or in combination, to meet the cooling needs of domestic dwellings. Due to the abundance of solar energy and the high ambient temperatures available in hot dry climates a direct solar cooling system could meet a large portion of the daily cooling load. Low energy technologies such as slab cooling can be employed to minimize the daily cooling load requirements, by utilizing diurnal variations in temperature. Low energy cooling technologies can also be used in the intermediate seasons of autumn and spring either to absorb the cooling load completely or reduce it drastically, depending on the requirements.

Further to the limitations/disadvantages of the low energy cooling technologies, presented in this paper and summarized in Table 1, the success of low energy cooling technologies depends greatly on environmental conditions like ambient temperature and humidity.

Low energy cooling technologies that require considerable amounts of water to operate, such as evaporative cooling systems, are not suitable for use in arid climates, which suffer from water shortages. Due to this fact water is usually very expensive.

During the design process, running costs of the low energy cooling technologies

Table 1
Main advantages and disadvantages of low energy cooling techniques

Cooling method	Advantages and disadvantages
Solar sorption cooling:	Generator temperature must be 70 °C–95 °C with water cooling in absorber and condenser
Lithium bromide-water ($LiBr-H_2O$)	COP 0.6–0.8 for single effect systems Evaporator cannot operate at temperatures below 5 °C
Ammonia-water (NH_3-H_2O) systems	A rectifying column must be present Generator temperatures must be 125 °C–170 °C with air-cooled absorber and condenser and 95 °C–120 °C when water cooling is used COP 0.6–0.7 for single effect systems
Desiccant cooling	Independent control of humidity and temperature Removal of certain airborne contaminants Ability to use energy sources such as waste heat, solar power and natural gas COP around 1.0
Solar-mechanical systems	Efficiency of photovoltaic panels is very low, about 10% The solar-powered prime mover combined with a Rankine engine has low efficiency about 17–23%. Very expensive system viable for very large applications Difficulty into ensuring that only vapour enters the turbine, since the boiler temperature changes during the day Not steady output power
Heat pumps	COP (useful effect/work done), between 2 and 5 Heat pumps can be used in combination with solar energy for heating
Natural night cooling	Unreliable air quality Unreliable air quantity Inefficient control of humidity and temperature Effective for building mass in excess of 800 kg/m^2 Provides sensible cooling only Effective in cool, dry to semi-humid climates Night air temperatures must be low (12–15 °C)
Mechanical night cooling	Good controllability of air flow and distribution Extra fun energy consumption Noise present, depending on air velocities Additional space needed for extra flow to existing buildings (false floors or cavities in buildings) Effective for building mass in excess of 800 kg/m^2 Provides sensible cooling only Used in commercial buildings

(*continued on next page*)

Table 1 (*continued*)

Cooling method	Advantages and disadvantages
Slab cooling	Reduction of mechanical cooling Utilization of off-peak electricity No need for suspended ceilings High levels of human comfort Slow thermal response to indoor load variations Higher maintenance cost due to leakages Provides sensible cooling only
Chilled ceilings	Reduction of refrigeration capacity Low energy consumption Good acoustics and indoor air quality Low maintenance costs Reduction in the space required for pure air ductwork in the ceiling void Risk of condensation High capital cost, at least 50% higher compared to conventional air-conditioning systems Possibility of water leakage in the ceiling installation Active cooling surface needed is 30 to 70 % of the total ceiling area
Direct evaporative air coolers	Provide relief or comfort cooling, depending on weather conditions and types of building Once-through airflow principle normally employed Used in residential applications Used in arid and semi-arid climates and relatively dry environments
Indirect evaporative air coolers	Provides sensible cooling only Provides relief or comfort cooling, depending on weather conditions and types of building Used in commercial buildings Used in arid and semi-arid climates and relatively dry environments

should be considered, against the price of electricity required to power ‘electrically-driven cooling equipment, which strongly depends on the way electricity is produced (e.g. wind energy, coal combustion, etc.).

The adoption of these technologies however, presents a considerable challenge to both building services’ engineers and architects.

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